Designing Experiments using Digital Fabrication in Structural Dynamics

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Abstract

In engineering, traditional approaches aimed at teaching concepts of dynamics to engineering students include the study of a dense yet sequential theoretical development of proofs and exercises. Seldom, structural dynamics are taught experimentally in laboratories since these facilities should be provided with expensive equipment such as wave generators, data-acquisition systems and heavily wired deployments with sensors. In this paper, the design of an experimental experience in the classroom based upon digital fabrication and modeling tools related to structural dynamics is presented. In particular, all experimental deployments are conceived with low-cost, open source equipment. Hardware includes Arduino-based open-source electronics whereas Software is based upon object-oriented open-source codes for the development of physical simulations. The set of experiments as well as the physical simulations are reproducible and scalable in classroom-based environments.

Introduction

For engineers of various areas, the study of vibrations and dynamics is an important cornerstone. In the particular case of civil and structural engineering, the vibration of beams and frames represent one of the first topics to be discussed in traditional courses of structural dynamics. Generally, these students have taken introductory and/or advanced courses of statics at this point of their curricula. Both dynamics and statics erect the frame of the vast field labeled in civil engineering as structural analysis. In dynamics, basic concepts such as damping, frequency, resonance or isolation are of an utmost importance when understanding more complex phenomena related to single- or multi-degree of freedom systems. Classic textbooks such as (Chopra 2007; Clough and Penzien 2003; Paz and Leigh 2003) provide detailed information about the basics, the development of the formulae as well as the application of such concepts in seismic and structural engineering.

Moreover, open electronics have become considerably popular among entrepreneurs, designers, computer scientists, hobbyists and more recently, engineering educators. A vast array of low-cost, open source microcontroller platforms such as (Arduino 2016, Raspberry Pi 2016 and Adafruit 2016) are nowadays commercially available and economically more affordable than professional equipment. These platforms, together with easy-to-use programming codes, allow bridging the existing physical-to-digital gap in civil engineering students. Simultaneously, it provides a low-cost source of creative technologies that may potentially be implemented in different educational ecosystems. Sensors and actuators of various sources can be coupled and controlled via i) open

platforms ii) free and/or commercial Software iii) open platforms aimed at developing mobile applications. Active online communities are nowadays feeding the web with endless possibilities related to coding, electronics and physical applications of such technologies. Together with additive 3D printing and subtractive laser-cutting, digital fabrication and modeling (DFM) is continuously entering into schools and universities as an important part of the curricula.

The aim of this paper is to present the design of a hands-on set of experiments related to structural dynamics. Teaching includes an initial understanding of DFM tools and the reproduction of a set of experiments related to structural dynamics developed with open-source Hardware and Software. The aim of the experimental experience is to provide to students tools related not only to structural dynamics but also, to creative DFM technologies. Particular goals of the proposal include:

- Providing a theoretical framework related to structural dynamics, including concepts of frequency, period, damping, resonance and the equations of motion.
- Providing concepts of the open prototyping platform Arduino and its circuitry.
- Providing an introduction to object-oriented physical simulations of dynamic systems using Processing 2.0 (Processing 2016), an open-source language and development environment built on top of the Java programming language.
- Providing initial computational tools for using Arduino and Processing as an open-source, low-cost data acquisition system that may be used in the classroom with scale-reduced experiments. Beams, frames and other structures may be excited dynamically and studied experimentally and numerically within the classroom.

Review of the earlier work.

Structural dynamics and education

The importance of structural dynamics gives the topic a major position in civil, mechanical and geological engineering. Classic textbooks with a vast array of exercises are available (Chopra 2007; Clough and Penzien 2003; Paz and Leigh 2003). Experimental dynamics in the particular case of beams also play a continuous primary role in textbooks (Blanco et al. 2007) and state-of-the-art research (Chen et al. 2014; Ozcelik et al. 2013; Adhikari et al. 2009). From an educational perspective, pedagogic platforms related to structural dynamics are not infrequent. Most of them are, however, based upon numerical simulations in desktop computers. Katsanos et al. (2014) developed educational computational tools for the seismic analysis of reinforced concrete. The platform was developed with Matlab (Matlab 2016) and accounts not only for the building structural dynamics but also, for the soil-structure interaction. With the aim of providing an educational learning environment for applications in dynamics, Elgamal et al. (2005) built shake-table tests involving web-based educational platforms and a vast number of exercises. The platform has been used in several universities in California and includes Hardware developed by the authors as well as visual tools developed with commercial Software Labview (2016). Senatore and Pikers (2015) developed an intuitive game-like platform for the understanding of structural analysis via 3D, FE-based models.

Use of open electronics and programming in engineering education

Experimental experiences have always been a cornerstone in civil engineering education (Solís et al. 2012; Chanson 2004; Unterweger 2005; Nakazawa 2014). The vast majority of civil engineering schools include classic experimental-based courses related to structures, materials, hydraulics, soils, and pavement engineering, among other subjects. However, educational tests in classic laboratories involve either expensive data-acquisition equipment that is seldom used by students in a "hands-on" mode or, more often, involve no equipment at all. Classic laboratories are generally conceived for small audiences. For large courses, measurements and control are usually performed by laboratory staff that provides raw data to students for further analysis. This is particularly common in large universities with a considerable amount of students or in countries in which laboratories are not equipped with sufficient material for both research and education. In particular, in civil engineering, at the end of their degrees, even if students are satisfactorily acquainted with the physical phenomena, a basic understanding of the electronics involved in measurement and data-acquisition is less frequent among them. These facts do not contribute to bridging the existing physical-to-digital gap among engineering students that is absolutely necessary to overcome in the digital society. With the advent of open platforms , students of other branches of engineering such as robotics (Valera et al. 2014), control engineering (Ionescu et al. 2013), real-time systems (Cruz-Martín et al. 2012) or chemistry (Guo et al. 2007) are increasingly acquainted with data-acquisition either with professional equipment or, via Do-it-Yourself (DIY) Hardware and Software. The convergence of 3D printing, open Hardware and open Software may revolutionize the educational experimental training nowadays provided in high schools as well as in technical universities (Pearce 2014). A deeper understanding of such possibilities may also help fostering entrepreneurial, innovative skills in civil engineering students in societies with no industrial manufacturing infrastructure (Fox 2014).

Examples of usage of open-source boards in engineering applications are not infrequent, particularly when coupled with wireless applications (Ferdoush and Li 2014). Control of experiments using Arduino boards and open source programming languages such as Python (2016) are available in platforms intended for physical and chemical experiments (Koenka et al. 2014) in a broader sense. In addition, open online communities and generators of content provide a vast array of blogs, web-based lectures and exercises to broader audiences (Shiffman 2016; MIT video website 2016; Coursera 2016).

Nevertheless, academic examples of applications of digital fabrication and open platforms in the particular case of civil engineering education are less abundant. Kensek (2014) explored the integration of sensors (providing analogic signals) with the digital control of architectural Software (based upon Building Information Modeling BIM) and viceversa using Arduino boards. This represents an example of the potential manipulation of physical architectural features of buildings (facades, windows, or similar) via Software-controlled tools. All these examples were designed and implemented in laboratories with students. Kensek demonstrates the back-and-forth nature of bridging the physical-to-digital gap using Arduino open platforms and the endless possibilities with the integration of BIM.

Software and Hardware

Processing and Arduino were chosen as the Software and Hardware combinations for the development of the educational experience due to availability at the school and the open-source nature of both. In addition, the Integrated Development Environment (IDE) of both platforms is very similar. Figure 1 shows both IDEs as well as a scheme of the coding syntaxes. Both cases include a *setup()* function (run once) and a *draw()* or *loop()* function, which runs repeatedly. For the case of Processing (Fig. 1(a)), the draw function allows developing computer simulations involving movement of objects. In the case of Arduino (Fig. 2(b)), the loop function defines all orders to be performed by the electrical flow designed with the corresponding circuitry.

Processing

Processing is an open-source language and development environment built on top of the Java programming language. It allows generating computer simulations and visual graphics from scratch (Reas and Fry 2014). In this context, Processing is used for developing object-oriented physics simulations. For this purpose, it is vital to get an initial understanding of motion in simple computational visual graphics.

One of the most efficient ways of developing simulations of motion of bodies according to physical laws is the use of an object-oriented approach. Classes that depict the behavior of objects such as balls, springs or rigid bodies may be defined separately. In the main code, new objects can be called and used by applying methods defined in the classes. Processing includes widely depicted in-built classes defining the behavior of vectors or images (PVector, PImage). The result is a simpler setup()-draw() code.

The Arduino board

Arduino is an open hardware-prototyping platform. Fig. 2 displays a sketch of the Arduino/Genuino UNO board, which may be deemed as the simplest kind of the Arduino products. A set of up to 6 analog and 13 digital pins are available in this board. Connection to computers is performed via USB (for uploading programs or providing power) and an alternative power supply connection (batteries or similar) may also be used in boards in which programs are already uploaded. The board is open and any program following the Arduino syntax can be uploaded and erased as needed. The board can be programmed to sense the environment by receiving analog inputs from many sensors, and/or to affect its surroundings by controlling lights, motors, and other actuators or digital devices.

The typical structure of Arduino programs is fairly simple can be divided in three main parts: structure, values (variables and constants), and functions. These functions require at least two parts, or blocks of statements. The *setup()* function is called when a sketch starts. It is used to initialize variables, pin modes, start using libraries, etc. The setup function will only run once, after each power up or reset of the Arduino board. After creating a *setup()* function, the *loop()* function which is repeated consecutively. Programming with the Arduino environment provides capabilities related to the Serial Port Communication, which allows user acquiring analog signals from sensors and microcontrollers to be sent to the computer (to be used in any application able to open that port reciprocally)

Class Methodology

For educational purposes, experimental tests with enriched content related to digital fabrication are conceived. This experience represents a part of a vaster course on structural dynamics including theoretical background and exercises presented in a classic fashion. The entire course consists of 15 sessions of 4 hours each (60 in total) and the experiments accounts for approximately a third (18 hours). The educational experience is conceived as hands-on with the use of computers, electronics and physical construction of 3D models. Lessons are separated in three main parts:

- Processing (6 hours). Introduction to OOVP with vectors and trigonometry and subsequently, simulation of two well-known dynamic systems, the pendulum and the spring.
- Arduino (6 hours). Introduction to Arduino circuitry by learning the basics, which include the control of a LED blink, introduction to sensing with Light Dependent Resistor LDR. Usage of the serial port to visualize analog magnitudes and the control of small motors and servos. Subsequently, design of two tests in simple cantilever beams.
- Scale reduced construction + Processing + Arduino (6 hours). Construction of a 3D frame in a hands-on experience. The frames are subsequently tested with a modal exciter and instrumented with Arduino. The obtained results are used and visualized. A comparison with theoretical analysis of n-degrees of freedom planar systems is performed for the sake of validation.

Table 1 displays the organization and schedule of the classroom as well as the educational activities that are suggested for the development of each part. From table 1 it is worth noticing:

- Master classes (Intro and Core) are given by the facilitator with a hands-on perspective for the first and second part. The students use desktop computers and electronic equipment in groups or individually. The third part is entirely driven by students as the constructors of 3D models.
- Homework (compulsory submission) are aimed at developing physical simulations or at analyzing physical results obtained in real models.

- Bonus (not compulsory) is a gamified feature of the experience, as an additional submission of creative projects. These creative projects may be also rewarded by featuring the results in social networks or in school days.

Finally, it is important to bear in mind that these 18 hours are part of a vaster course (60 hours in total) in which traditional lectures and evaluations are performed.

In the following, details concerning each part of the designed class classroom are provided.

Physical simulations. Pendulum and Spring.

First, a 2-hour long introduction related to motion, vectors, location, velocity and acceleration is presented. This part is needed for the sake of developing an interactive trial-and-error coding strategy with immediate feedback of results with the students. The mathematics related to all the depicted aspects are customized by students from scratch. The location of an object (rectangle, circle,

pixel) is expressed in terms of its planar coordinates, time and its velocity. The velocity of such object is expressed in terms of the acceleration (two-dimensions). Similarly, the angular position, velocity and acceleration of a given object define the rotation in time.

After all initial information related to vectors and to trigonometry is depicted with the corresponding motion equations, the main core of this part is the development of two different dynamic systems: A pendulum and a spring.

For the former, the students need to use basic concepts related to vectors and trigonometry for the development of a simple yet realistic physical simulation of a moving object whose position is repeatedly updated. At each frame, forces are applied to the object (self-weight, damping and anchor) and thus, acceleration, velocity and location of the object are updated. Figure 3 displays the result obtained by students in the Processing canvas as well as a scheme of the applied forces.

For the latter, the students need to use concepts related to Hooke's law for the development of a simple yet realistic physical simulation of a moving spring whose position is repeatedly updated. At each frame, the self-weight and the spring force are applied to the object and thus, acceleration, velocity and location of the object are updated. Figure 4 displays the result obtained by students in the Processing canvas as well as a scheme of the applied forces.

Mastering such simulations is cornerstone for the students from two perspectives:

- The students are required to submit a compulsory homework in which a more sophisticated simulation is assigned. Beams, Frames or multi-springs systems are visually simulated (all systems with a single degree of freedom).

- The students get acquainted with the object-oriented syntaxes of Processing, which is similar and subsequently, easier to follow in Arduino IDE.

Physical experiments. Free vibrations and harmonic oscillations

First, a 2-hour long introduction related to basic electronics is presented. The students are provided with kits containing the following equipment:

- Arduino UNO board with USB cable
- Light dependent resistors (LDR)
- A potentiometer
- Buttons
- A breadboard
- A 3-axis accelerometer
- A small 9V motor and a servomotor
- 330Ω, 1k Ω and 10k Ω resistor, a Mosfet transistor and cables.

The intro is conceived as a trial-and-error hands-on experience of the students developing basic circuitries and codes. The main idea is to provide tools and exercises that allow students answering the following questions:

- How to obtain an analog magnitude from an accelerometer using an Arduino Board and plotting the results in a Desktop/Laptop computer?
- How to visualize acceleration values from an excited system in real time?
- How to control a 5V motor with an Arduino Board by using controllers such as buttons and potentiometers?

The core of this part is the design of two experiments: i) Free vibrations and ii) harmonic excitations in structural systems. Both experiments are performed in a cantilever steel beam of varying length and rectangular cross-section 20mmx4mm. The steel plate is connected to a rigid table with adjustable clamping devices. Thus, students can manipulate the steel plate and adjust its length. In both experiments, a three-axis accelerometer is connected to an Arduino board. In experiment 1 (free vibrations, Fig. 5), an initial displacement u_0 is applied in the tip of the cantilever. The system vibrates freely for several seconds. In experiment 2 (Fig. 6), an Arduino-controlled eccentric rotor excites the system in a harmonic way. The speed of the motor is controlled with buttons and a potentiometer. Finally, schemes of the circuitries that are used for acquiring values of acceleration (Fig. 7(a)) and for controlling an actuator (a small motor) are provided (Fig. 7(b))

Hands-on construction and instrumentation of 3D frames.

The educational experience includes the construction of 3D frames using steel bars, plastic bars (polyamide), methacrylate plates for slabs, bolts and nuts and a rigid plate for the base. These elements offer versatility. Additional masses and varied geometry (height and number of stories) can be achieved by students. The students are given initial conditions to design their buildings: the structure should have a natural frequency ranging from 1Hz to 10Hz and a maximum of 5 kilograms. The lab facilities include a scale-reduced shaking table in which structures with such maximum characteristics may be tested. Consequently, the students use numerical concepts presented in the theoretical part of the course for designing the buildings. The students calculate the natural frequency of a 2-3 degrees of freedom system and play with the variables height, material, number of stories, and added mass. Fig. 8 shows the construction phases of such building in past editions of the educational experience.

Subsequently, the models are tested with 2D axis accelerometers at each story. The base motion is generated with a scale reduced modal exciter available in the laboratory facilities. The exciter provides a 0-20Hz range available for frequency sweep. The base of each frame is clamped to the moving table. Harmonic amplified signals are provided to the actuator at varying values of frequency in order to analyze different vibration modes as well as in order to measure acceleration at each story. Resonance as well as different modes are activated for certain frequency values. Furthermore, the experience illustrates to the students how unavoidable misalignments during the frame construction may lead to undesired torsional modes. Figure 9 shows a scheme as well as a lateral view of the test deployment.

Discussion of the educational experience

The educational experience has been implemented in small groups ranging from 4 to 15 students from a Master Course of Construction Engineering. The methodology of some of these previous editions was not identical though. The results obtained so far when applying the depicted methodology prove satisfactory for small groups. Submissions of the compulsory homework are correct and their quality is remarkable. In small groups, however, the bonus submissions are not numerous so far. Figure 10 displays screenshots adapted from some examples of physical simulations. Moving frames, beams and pendulum are the main simulated systems. Concepts of damping, resonance, frequency and motion are inferred and studied from simulations. Figure 11 displays images of the experiments (both cantilever and frame) and some of the results submitted by students in form of adapted plots. During these experiences, the students face typical situations related to experimental mechanics such as: validation of results and difference between theory and tests, which is very valuable as an educational experience for the particular case of structural dynamics. The students analyzed different alternatives to which these discrepancies may be attributed to. Imperfect clamping of the elements, imperfect horizontality of the sensors and/or frame elements or asymmetries are generally the main reasons of these differences.

One key aspect of the educational experience is the feedback from students. Since this course also includes hours of theory and exercises within a regular classroom, it is possible to check the experimentally obtained results with those derived theoretically. As a result, a validation process is performed by students. It is worth pointing out that this validation process is useful not only for its own sake, but also, for testing the educational capabilities of the experience as a whole. When results obtained match, the students gain self-confidence about the whole experience. If conversely, these results do not match, students are entitled to enquire about potential mistakes (either theoretical or experimental). Concepts and methods are revisited and the educational experience is enriched.

Finally, it is worth pointing out that a more systematic assessment of the experience, including objective standard evaluation of the pedagogy is necessary if implemented in larger groups. Likewise, the extra activities suggested in table 1 as bonuses, are more likely to be performed by students in larger groups than in smaller ones.

Reproduction of similar experience in classroom-based environments

Similar educational experiences using DFM and physical simulations are feasible not only for structural dynamics but also for a broader scope of subjects. Processing and Arduino present a very similar programming environment and sending values from real sensors to Processing as input parameters is intuitive using OOVP. In this particular case, the animations consist of bodies in which acceleration changes velocity and velocity changes their location with time. These values of acceleration may be collected in real time from external sources or alternatively, defined by the user internally in the code. In other simple systems in which any animation variable may be defined by external inputs, Processing and Arduino match satisfactorily.

Arduino-wise, the key aspect in the experience is to teach how to collect analog magnitudes from sensors. This process is relatively straightforward. Values obtained with potentiometers or light dependent resistors are useful for beginners since these magnitudes can be altered and understood easily by the users. Once the signal magnitudes are collected, the key issue is to send it via serial port to the computer to be collected by Software. In Processing, an Arduino object must be declared and thus, methods related to collecting analog values from sensors can be applied to these objects. In this particular set of experiments, the construction part involves “hands-on” experimental hours with previous design of a structure using theoretical and numerical tools. The most important aspect in this part is to conceive a structure that may be excited appropriately by the laboratory facilities.

Conclusions

In this paper, a design of an experimental experience related to structural dynamics based upon DFM tools is presented. The classroom is designed in such a way that first, the students get acquainted with physics simulations using open-source codes. Second, a set of experiments with teaching purposes related to structural dynamics is reproduced using open-source low-cost electronics and third, a hands-on experience related to construction and instrumentation of scale-reduced 3D building is performed. Several conclusions can be drawn from this work:

- From the structural analysis perspective, the experiments are designed with open-electronics platforms and easy-to-follow Software. The experiments may be useful in basic courses of structural dynamics with a particular emphasis on the behavior of structural systems subjected to free vibrations and to harmonic oscillations. Concepts such as damping, sweep frequency response analysis and resonance can be analyzed experimentally. The experiments can be performed in a classroom-based environment and if needed, the entire preparation of the material can be performed by students from scratch.

- From the engineering education perspective, the design of such experiments may provide added value to students in a manifold fashion: i) Students may start bridging the existing physical-to-digital gap in civil engineering schools. ii) Students may start fostering the potential entrepreneurial attitude that digital fabrication and open-source labs are expected to generate. iii) Students may start getting acquainted with the development of object oriented physics simulations with open platforms. Such tools are not yet universally known and used in civil engineering schools.

- Education-wise, the experience includes a theory vs. experiments validation, which gives hints to the students and facilitators about the quality of the results but also, about the understanding of concepts. Indirectly, the educational experience is tested via this particular validation.

- As the main objective of the educational research, it is worth pointing out that the development of experiments using low-cost and easy-to-implement platforms may result in a profuse ecosystem of possibilities, in which students are focused in building their own theoretical framework via experimental design, rather than in classical lectures. Educators may divert the focus of such classical lectures to more "hands-on" experiences and to proper assistance of students during teaching hours. This is particularly interesting since increasingly, the design of experiments is in high demand by the societal changes in education.

- The educational experience provides insight of new technologies to civil engineering students. Electronics and object-oriented programming are seldom in classical curricula. An introduction to such topics, however, is necessary since increasingly, civil engineering professionals participate in construction and the internet of things using embedded technologies related to structural health monitoring as well as to automation.

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List of tables and figures (Captions)

Fig. 1. Processing (a) and Arduino (b) Integrated Development Environment

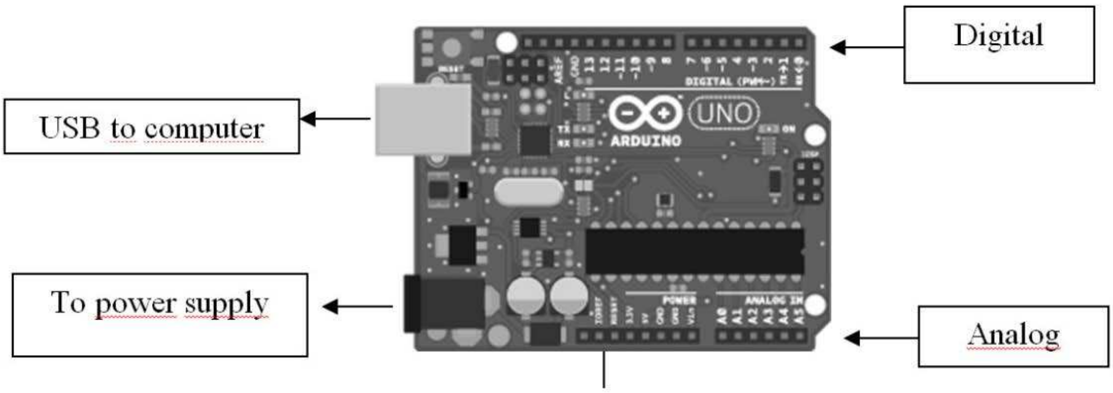

Fig. 2. The Arduino/Genuino UNO board.

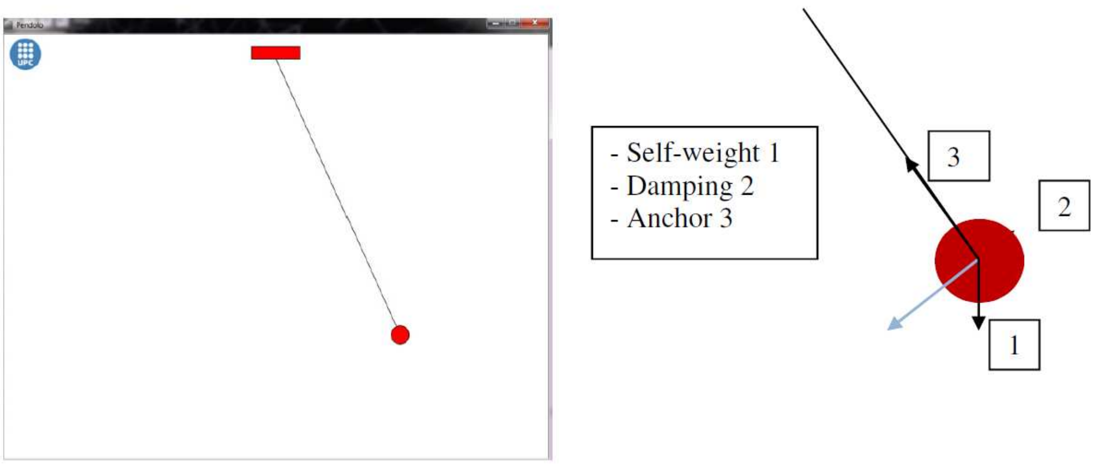

Fig. 3. Pendulum in processing. Anchor, rod and mass.

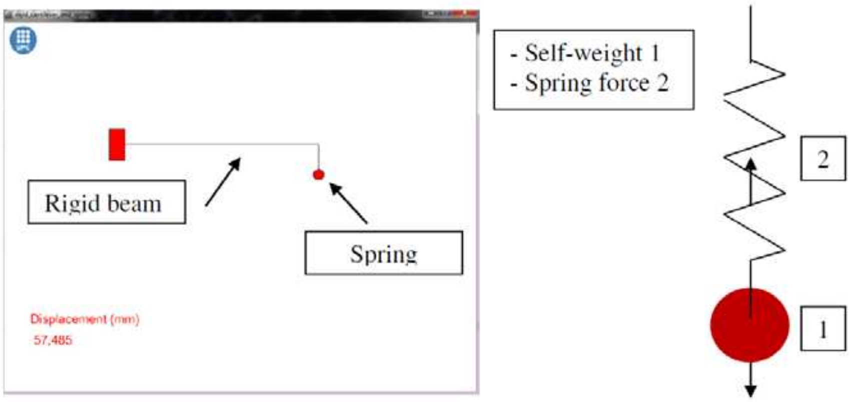

Fig. 4. Spring in Processing. Rigid beam, spring and mass.

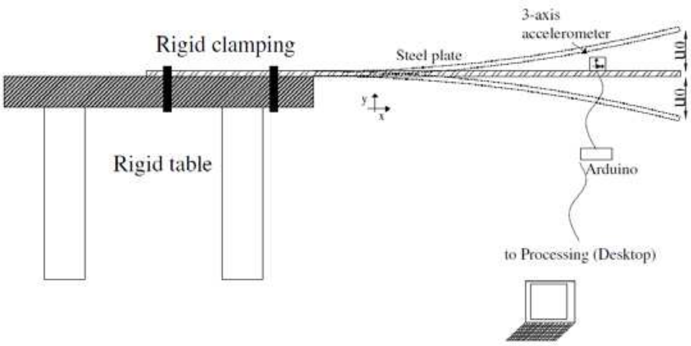

Fig. 5. Free vibrations. Connections and general view of the experimental setup

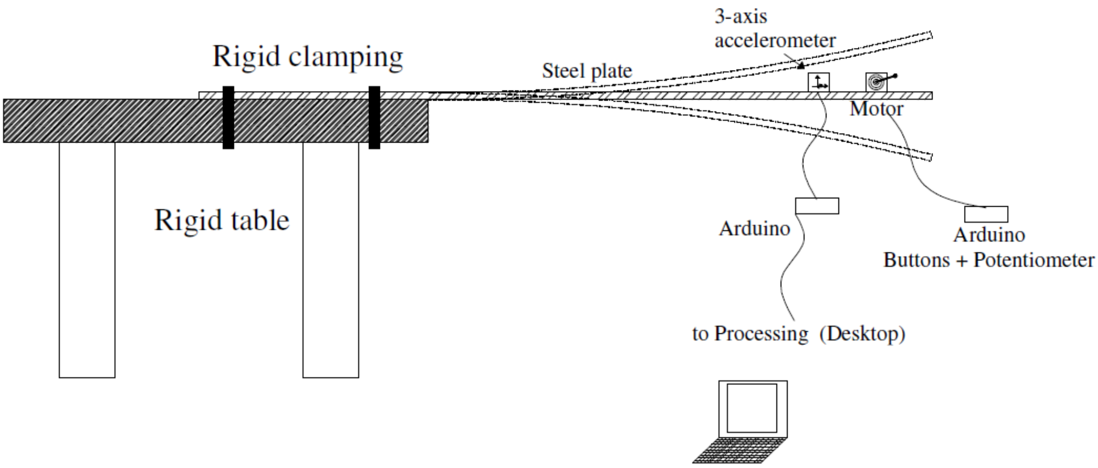

Fig. 6. Harmonic oscillations. Connections and general view of the experimental setup

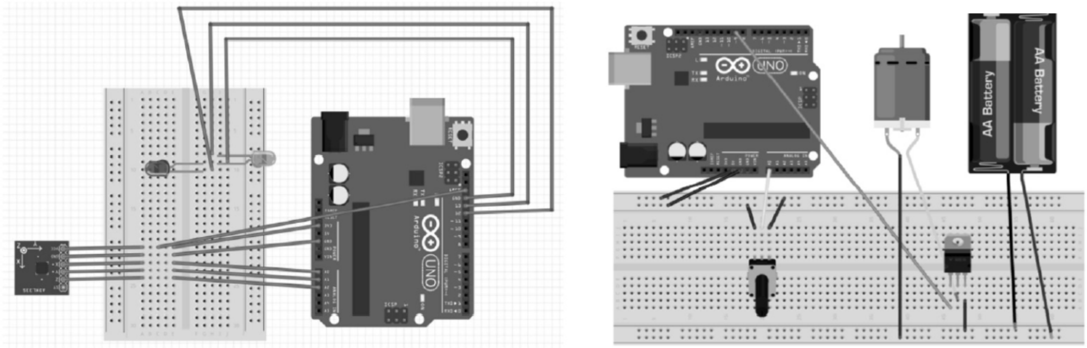

Fig. 7. Arduino circuitries (a) Acquiring acceleration analog magnitudes (b) Control of actuator

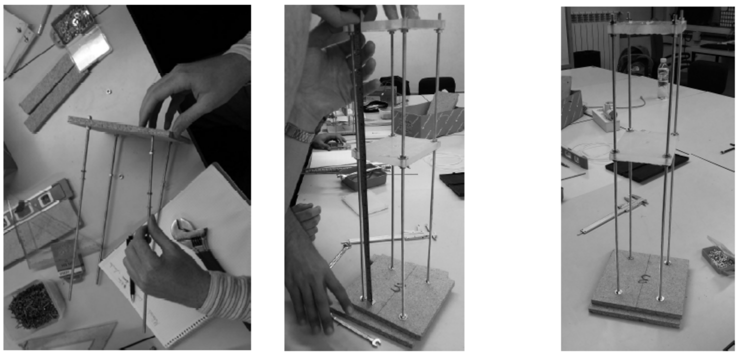

Fig. 8. Construction of 3D frames with variable materials, masses and geometries

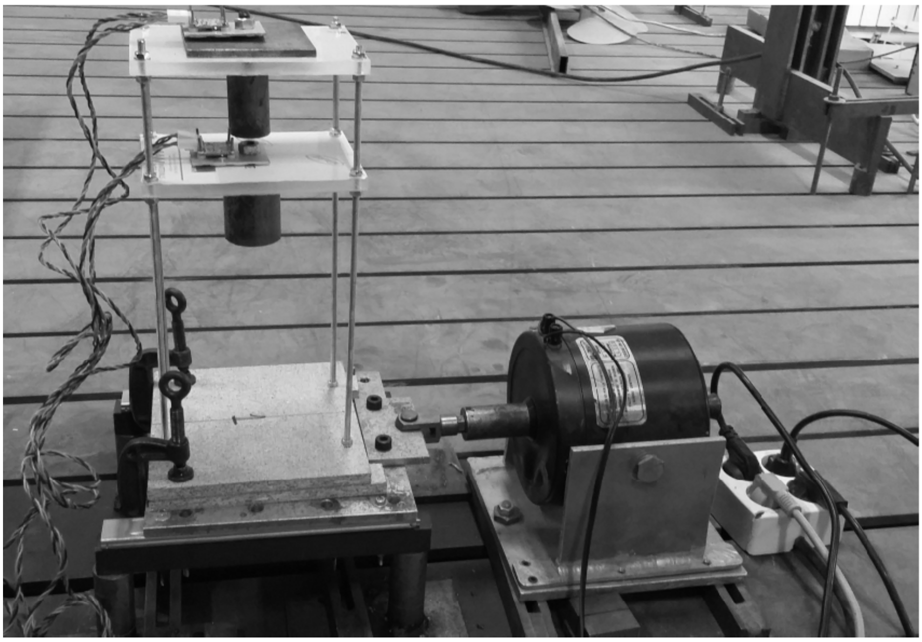

Fig. 9. Scale-reduced test of 3D frames subjected to harmonic oscillations

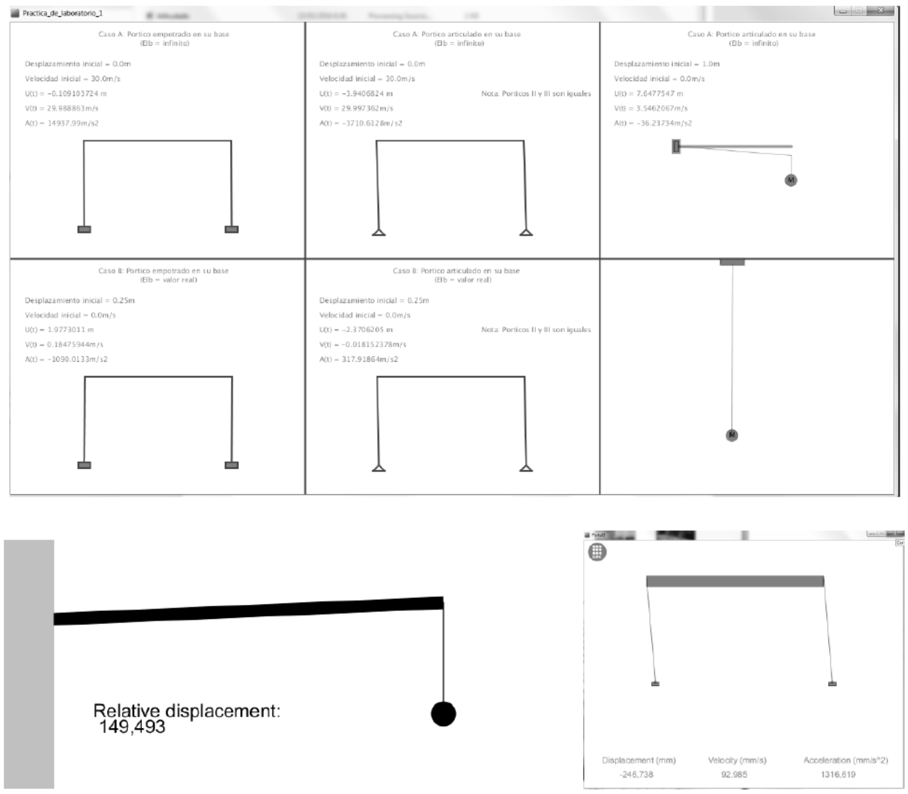

Fig. 10. Drawings adapted from submitted codes including frames, beams and springs.

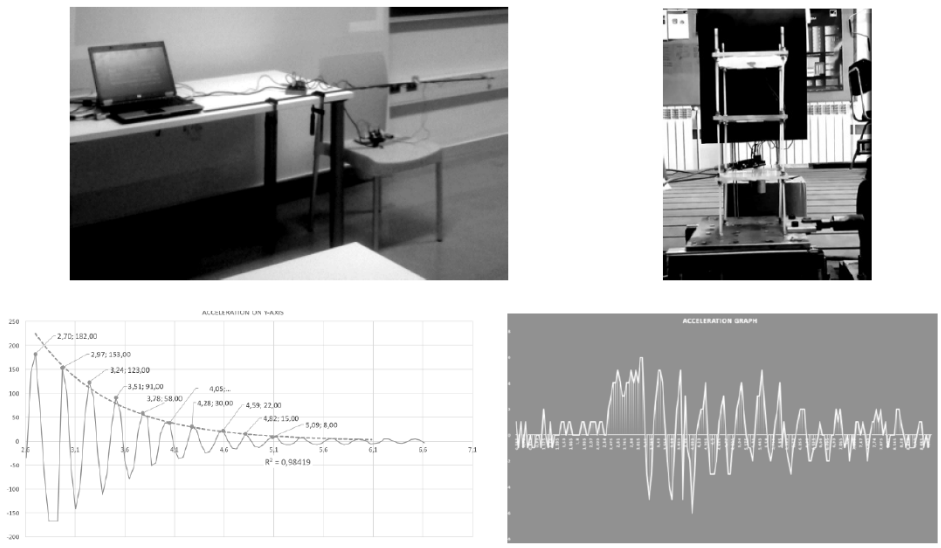

Fig. 11. Illustrative results adapted from submitted data

Intro 2 hours	**Intro** 2 hours	**Intro** 2 hours
Object-Oriented visual programming (OOVP) Vectors and Trigonometry in Processing	Basic circuitry. Blink a LED, Use a light sensor, Use a potentiometer, Activate a small motor or servo motor	Building 3D frames using basic tools and materials such as steel bars, plastic plates, screws, nuts. Hands-on experience
Core 4 Hours	**Core** 4 Hours	**Core** 4 Hours
OOVP. The pendulum OOVP. The spring	Test. Free vibrations of a cantilever Test. Harmonic excitations of a cantilever	Instrumentation and connection to a moving table coupled to a modal exciter. Test the system for various frequencies
Homework	**Homework**	**Homework**
Individual submission	1 , 2 , 3 up to 4 students	1 , 2 , 3 up to 4 students
Submission an animation of a more complex multi-pendula or multi-spring system concerning	Submission an in-depth analysis of the used equipment as well as the results obtained with particular focus on:	Submission an in-depth analysis of the dynamic behavior of their own structure with particular focus on:
Motion / Force / Acceleration	Frequency / Damping / Resonance	n-modes / Acceleration / Resonance
one degree of freedom	one degree of freedom	n-degrees of freedom
Bonus	**Bonus**	**Bonus**
Creative animation	Calibration of the accelerometers	Creative simulations
Submission an animation including images or other additional features to add realism	Additional features for the control of the motors. Use of mobile applications	Real-time use of the measured values for developing realistic animations

Table 1. Organization of the educational experience